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6. AUTHORS
Han Pu, Randall G. Hulet

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
William Marsh Rice University
6100 Main Street

Houston, TX 77005 -1827

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14. ABSTRACT
Ultracold atoms confined in optical lattice potentials provide an ideal platform to address some of the most outstanding questions in quantum many-body physics, that are difficult or impossible to study using conventional solid state systems. During this DARPA program, progress in several important directions has been made. We have developed cooling techniques suitable for a lattice system and cooled fermionic lithium atoms confined in a three-dimensional (3D) cubic lattice to unprecedented low temperatures, very close to the Néel temperature. We employed Bragg scattering of near-resonant light to observe the antiferromagnetic correlations. We have mapped

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Report Title

Final Report: Quantum Phases of Matter in Optical Lattices

ABSTRACT

Ultracold atoms confined in optical lattice potentials provide an ideal platform to address some of the most outstanding questions in quantum many-body physics, that are difficult or impossible to study using conventional solid state systems. During this DARPA program, progress in several important directions has been made. We have developed cooling techniques suitable for a lattice system and cooled fermionic lithium atoms confined in a three-dimensional (3D) cubic lattice to unprecedented low temperatures, very close to the Néel temperature. We employed Bragg scattering of near-resonant light to observe the antiferromagnetic correlations. We have mapped the phase diagram over the entire BEC-BCS crossover for a trapped 3D gas with imbalanced numbers of spin-up and spin-down atoms, and have also observed the crossover from a 1D to a 3D spin-imbalanced Fermi gas. We have investigated dynamics, rethermalization and out-of-equilibrium phenomena in strongly correlated lattice systems, as well as in disordered lattice systems. These studies greatly deepened our understanding of quantum phases of matter in lattice potentials.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
05/28/2015 44.00	Sangwoo S. Chung, Kuei Sun, C. J. Bolech. Matrix product ansatz for Fermi fields in one dimension, Physical Review B, (03 2015): 0. doi: 10.1103/PhysRevB.91.121108
05/28/2015 55.00	Ushnish Ray, Stefan Natu, Philip Russ, David Ceperley, David McKay, Brian DeMarco. Metastable Bose-Einstein condensation in a strongly correlated optical lattice, Physical Review A, (2 2015): 0. doi: 10.1103/PhysRevA.91.023625
05/28/2015 54.00	S.?S. Kondov, W.?R. McGehee, W. Xu, B. DeMarco. Disorder-Induced Localization in a Strongly Correlated Atomic Hubbard Gas, Physical Review Letters, (2 2015): 0. doi: 10.1103/PhysRevLett.114.083002
05/28/2015 53.00	Ying Dong, Lin Dong, Ming Gong, Han Pu. Dynamical phases in quenched spin–orbit-coupled degenerate Fermi gas, Nature Communications, (01 2015): 0. doi: 10.1038/ncomms7103
05/28/2015 52.00	Hui Hu, Lin Dong, Ye Cao, Han Pu, Xia-Ji Liu. Gapless topological Fulde-Ferrell superfluidity induced by an in-plane Zeeman field, Physical Review A, (09 2014): 0. doi: 10.1103/PhysRevA.90.033624
05/28/2015 51.00	Russell A. Hart, Pedro M. Duarte, Tsung-Lin Yang, Xinxing Liu, Thereza Paiva, Ehsan Khatami, Richard T. Scalettar, Nandini Trivedi, David A. Huse, Randall G. Hulet. Observation of antiferromagnetic correlations in the Hubbard model with ultracold atoms, Nature, (02 2015): 0. doi: 10.1038/nature14223
05/28/2015 50.00	Pedro M. Duarte, Russell A. Hart, Tsung-Lin Yang, Xinxing Liu, Thereza Paiva, Ehsan Khatami, Richard T. Scalettar, Nandini Trivedi, Randall G. Hulet. Compressibility of a Fermionic Mott Insulator of Ultracold Atoms, Physical Review Letters, (02 2015): 0. doi: 10.1103/PhysRevLett.114.070403
05/28/2015 49.00	Rahul Nandkishore, Vadim Oganesyan, David A. Huse. Phenomenology of fully many-body-localized systems, Physical Review B, (11 2014): 0. doi: 10.1103/PhysRevB.90.174202
05/28/2015 48.00	Merritt C. Kerridge, David A. Huse, Bo Zhao. Three species of Schrödinger cat states in an infinite-range spin model, Physical Review E, (08 2014): 0. doi: 10.1103/PhysRevE.90.022104
05/28/2015 47.00	Xiaopeng Li, Biao Wu, W Vincent Liu, Bo Liu. Chiral superfluidity with p-wave symmetry from an interacting s-wave atomic Fermi gas, Nature Communications, (09 2014): 0. doi: 10.1038/ncomms6064
05/28/2015 46.00	Bo Liu, Xiaopeng Li, Lan Yin, W. Vincent Liu. Weyl Superfluidity in a Three-Dimensional Dipolar Fermi Gas, Physical Review Letters, (01 2015): 0. doi: 10.1103/PhysRevLett.114.045302
05/28/2015 45.00	Zhi-Fang Xu, Xiaopeng Li, Peter Zoller, W. Vincent Liu. Spontaneous Quantum Hall Effect in an Atomic Spinor Bose-Fermi Mixture, Physical Review Letters, (03 2015): 0. doi: 10.1103/PhysRevLett.114.125303

05/29/2015 56.00 Tin-Lun Ho, Biao Huang. Local spin structure of large spin fermions,
Physical Review A, (4 2015): 0. doi: 10.1103/PhysRevA.91.043601

05/29/2015 58.00 Xiaoling Cui, Tin-Lun Ho. Ground-state ferromagnetic transition in strongly repulsive one-dimensional Fermi gases,
Physical Review A, (2 2014): 0. doi: 10.1103/PhysRevA.89.023611

05/29/2015 57.00 Xiaoling Cui, Tin-Lun Ho. Spin-orbit-coupled one-dimensional Fermi gases with infinite repulsion,
Physical Review A, (1 2014): 0. doi: 10.1103/PhysRevA.89.013629

07/31/2014 32.00 D. Chen, C. Meldgin, B. DeMarco. Bath-induced band decay of a Hubbard lattice gas,
Physical Review A, (07 2014): 0. doi: 10.1103/PhysRevA.90.013602

07/31/2014 42.00 Kuei Sun, C. J. Bolech. Bose-Hubbard model with occupation-parity couplings,
Physical Review B, (02 2014): 0. doi: 10.1103/PhysRevB.89.064506

07/31/2014 41.00 Bhuvanesh Sundar, Erich J. Mueller. Universal quantum computation with Majorana fermion edge modes through microwave spectroscopy of quasi-one-dimensional cold gases in optical lattices,
Physical Review A, (12 2013): 0. doi: 10.1103/PhysRevA.88.063632

07/31/2014 40.00 Junjun Xu, Qiang Gu, Erich J. Mueller. Route to observing topological edge modes in ultracold fermions,
Physical Review A, (01 2014): 0. doi: 10.1103/PhysRevA.89.013625

07/31/2014 38.00 Hyungwon Kim, David A. Huse. Ballistic Spreading of Entanglement in a Diffusive Nonintegrable System,
Physical Review Letters, (09 2013): 0. doi: 10.1103/PhysRevLett.111.127205

07/31/2014 35.00 Xiaopeng Li, Arun Paramekanti, Andreas Hemmerich, W. Vincent Liu. Proposed formation and dynamical signature of a chiral Bose liquid in an optical lattice,
Nature Communications, (02 2014): 0. doi: 10.1038/ncomms4205

07/31/2014 34.00 Xiaopeng Li, W. Vincent Liu, Leon Balents. Spirals and Skyrmions in Two Dimensional Oxide Heterostructures,
Physical Review Letters, (02 2014): 0. doi: 10.1103/PhysRevLett.112.067202

09/04/2013 1.00 David A. Huse, Rahul Nandkishore, Vadim Oganesyan, Arijeet Pal, S. L. Sondhi. Localization-protected quantum order,
Physical Review B, (07 2013): 0. doi: 10.1103/PhysRevB.88.014206

09/04/2013 2.00 Lin Dong, Lei Jiang, Han Pu. Fulde–Ferrell pairing instability in spin–orbit coupled Fermi gas,
New Journal of Physics, (07 2013): 0. doi: 10.1088/1367-2630/15/7/075014

09/04/2013 4.00 Ying Dong, Han Pu. Spin mixing in spinor Fermi gases,
Physical Review A, (04 2013): 0. doi: 10.1103/PhysRevA.87.043610

09/04/2013 3.00 Lei Jiang, Hui Hu, Han Pu, Lin Dong. Finite-momentum dimer bound state in a spin-orbit-coupled Fermi gas,
Physical Review A, (04 2013): 0. doi: 10.1103/PhysRevA.87.043616

09/04/2013 5.00 B. Ramachandhran, Hui Hu, Han Pu. Emergence of topological and strongly correlated ground states in trapped Rashba spin-orbit-coupled Bose gases,
Physical Review A, (03 2013): 0. doi: 10.1103/PhysRevA.87.033627

09/04/2013 6.00 Lu Zhou, Han Pu, Weiping Zhang. Anderson localization of cold atomic gases with effective spin-orbit interaction in a quasiperiodic optical lattice,
Physical Review A, (02 2013): 0. doi: 10.1103/PhysRevA.87.023625

09/04/2013 7.00 Hui Hu, Lei Jiang, Han Pu, Yan Chen, Xia-Ji Liu. Universal Impurity-Induced Bound State in Topological Superfluids,
Physical Review Letters, (01 2013): 0. doi: 10.1103/PhysRevLett.110.020401

09/04/2013 8.00 Yong Xu, Zhu Chen, Hongwei Xiong, W. Vincent Liu, Biao Wu. Stability of p-orbital Bose-Einstein condensates in optical checkerboard and square lattices,
Physical Review A, (01 2013): 0. doi: 10.1103/PhysRevA.87.013635

09/04/2013 9.00 Xiaopeng Li, W. Vincent Liu. Orbital coupled dipolar fermions in an asymmetric optical ladder,
Physical Review A, (06 2013): 0. doi: 10.1103/PhysRevA.87.063605

09/04/2013 10.00 Xiaopeng Li, Erhai Zhao, W. Vincent Liu. Topological states in a ladder-like optical lattice containing ultracold atoms in higher orbital bands,
Nature Communications, (02 2013): 0. doi: 10.1038/ncomms2523

09/04/2013 15.00 Erich J. Mueller, Veit Elser, Yariv Yanay. Magnetic polarons in two-component hard-core bosons,
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09/04/2013 16.00 Ran Wei, Erich J. Mueller. Magnetic-field dependence of Raman coupling in alkali-metal atoms,
Physical Review A, (04 2013): 0. doi: 10.1103/PhysRevA.87.042514

09/04/2013 17.00 Ran Wei, Erich J. Mueller. Majorana fermions in one-dimensional spin-orbit-coupled Fermi gases,
Physical Review A, (12 2012): 0. doi: 10.1103/PhysRevA.86.063604

09/04/2013 18.00 Stefan S. Natu, Erich J. Mueller. Dynamics of correlations in a dilute Bose gas following an interaction quench,
Physical Review A, (05 2013): 0. doi: 10.1103/PhysRevA.87.053607

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Physical Review A, (06 2013): 0. doi: 10.1103/PhysRevA.87.063616

09/05/2013 24.00 Xiaoling Cui, Tin-Lun Ho. Phase Separation in Mixtures of Repulsive Fermi Gases Driven by Mass Difference,
Physical Review Letters, (04 2013): 0. doi: 10.1103/PhysRevLett.110.165302

09/05/2013 23.00 Xiaoling Cui, Biao Lian, Tin-Lun Ho, Benjamin L. Lev, Hui Zhai. Synthetic gauge field with highly magnetic lanthanide atoms,
Physical Review A, (07 2013): 0. doi: 10.1103/PhysRevA.88.011601

09/05/2013 21.00 Aaron Reinhard, Jean-Félix Riou, Laura A. Zundel, David S. Weiss, Shuming Li, Ana Maria Rey, Rafael Hipolito. Self-Trapping in an Array of Coupled 1D Bose Gases,
Physical Review Letters, (1 2013): 0. doi: 10.1103/PhysRevLett.110.033001

09/05/2013 20.00 Shuming Li, Salvatore R. Manmana, Ana Maria Rey, Rafael Hipolito, Aaron Reinhard, Jean-Félix Riou, Laura A. Zundel, David S. Weiss. Self-trapping dynamics in a two-dimensional optical lattice,
Physical Review A, (8 2013): 0. doi: 10.1103/PhysRevA.88.023419

09/06/2013 25.00 David M. Ceperley, Ushnish Ray. Revealing the condensate and noncondensate distributions in the inhomogeneous Bose-Hubbard model,
Physical Review A, (5 2013): 0. doi: 10.1103/PhysRevA.87.051603

09/07/2013 26.00 Kuei Sun, C. J. Bolech. Pair tunneling, phase separation, and dimensional crossover in imbalanced fermionic superfluids in a coupled array of tubes,
Physical Review A, (5 2013): 0. doi: 10.1103/PhysRevA.87.053622

09/07/2013 27.00 C J Bolech,, F Heidrich-Meisner, S Langer, I P McCulloch, G Orso, M Rigol. Expansion after a geometric quench of an atomic polarized attractive Fermi gas in one dimension,
Journal of Physics: Conference Series, (02 2013): 0. doi: 10.1088/1742-6596/414/1/012033

09/07/2013 28.00 William S. Cole, Shizhong Zhang, Arun Paramekanti, Nandini Trivedi. Bose-Hubbard Models with Synthetic Spin-Orbit Coupling: Mott Insulators, Spin Textures, and Superfluidity,
Physical Review Letters, (8 2012): 0. doi: 10.1103/PhysRevLett.109.085302

TOTAL: **45**

Number of Papers published in peer-reviewed journals:

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(c) Presentations

Bath-induced band-decay in a spin-dependent optical lattice, B. DeMarco, D. Chen. C. Meldgin, DAMOP 2013

Disordered Hubbard model with ultracold atoms, W. R. McGehee, S. Kondov, B. DeMarco, DAMOP 2013

3D Anderson Localization in Variable Scale Disorder, W. Xu. W. R. McGehee, S. S. Kondov, J. J. Zirbel, and B. DeMarco, Boulder School for Condensed Matter and Materials Physics, 2013

Interplay of disorder and interactions in an Optical Lattice Hubbard Model, W. R. McGehee, S. S. Kondov, and B. DeMarco, Gordon Conference on Atomic Physics, 2013

Bath-induced Band Decay and Quasimomentum Cooling in an Optical Lattice, C. Meldgin, D. Chen, and B. DeMarco, Gordon Conference on Atomic Physics, 2013

Ultracold Fermions in a Disordered Optical Lattice, S. Kondov, Physics of Quantum Electronics conference 2013

Controlled Dynamics in Disordered Quantum Gases, B. DeMarco, KITP conference on New Directions in the Quantum Control Landscape, 2013

Localized Impurities in Ultracold Fermi Gas, Han Pu, Hangzhou Workshop on Quantum Matter, 2013

Ground State and Expansion Dynamics of a One-Dimensional Fermi Gas, Han Pu, Wolfgang Pauli Institute Workshop on Confined Quantum Systems: Modeling, Analysis and Computation, 2013

Rashba Spin-Orbit Coupled Bose Gases: Perspectives from MF and ED Studies, Ramachandhran Balasubramanian, DARPA Workshop on Optical Lattice Emulator, 2012

Universal Impurity-Induced Bound State in Topological Superfluids, L. Jiang, H. Hu, X.-Ji. Liu, H. Pu, and Y. Chen, DAMOP, 2013

Anderson Localization of Cold Atomic Gas with Effective Spin-Orbit Interaction in a Quasiperiodic Optical Lattice, L. Zhou, W. Zhang, and H. Pu, APS March Meeting 2013

FF Pairing Instability in Spin-Orbit Coupled Fermi Gas, L. dong, L. Jiang, H. Hu and H. Pu, APS March Meeting 2013

Topological and Strongly Correlated Ground States in Rashba Spin-Orbit Coupled Bose Gases, R. Balasubramanian, H. Hu and H. Pu, APS March Meeting 2013

Randall G. Hulet, “Hubbard Model with Ultracold Atoms: Observation of Antiferromagnetic Correlations”, Frontiers of Quantum and Mesoscopic Thermodynamics Meeting, Prague, Czech Republic (7/31/13).

Randall G. Hulet, “Optical Lattice Simulations of Correlated Fermions”, DARPA OLE Workshop, San Francisco (5/30/13).

Randall G. Hulet, “Quantum Simulations with Atoms in Optical Lattices”, Workshop on New Magnetic Field Frontiers in Atomic/Molecular and Solid State Physics, Les Houches, France (5/6/13).

Randall G. Hulet, “Quantum Simulations with Atoms in Optical Lattices”, Workshop on Quantum Matter, Hangzhou, China (4/23/13).

Randall G. Hulet, “Quantum Simulations with Atoms in Optical Lattices”, Symposium on Cold Atom Physics, Shanghai Center for Complex Physics, Shanghai, China (4/19/13).

Randall G. Hulet, “Few Body Physics with Ultracold Atoms – The Efimov Family Tree”, International Conference on Few-Body Physics in Cold Atoms, Beijing (4/11/13).

Randall G. Hulet, “Atoms in Optical Lattices – the Hydrogen Atom of Many-Body Physics”, Symposium Honoring Daniel Kleppner, Sao Carlos, Brazil (2/28/13).

Randall G. Hulet, “Quantum Simulations with Atoms in Optical Lattices”, Symposium on Novel Topological Quantum Matter”, University of Texas, Dallas, TX (2/25/13).

Randall G. Hulet, “Quantum Simulations with Atoms in Optical Lattices”, Physics of Quantum Electronics Conference, Snowbird, UT (1/7/13).

Randall G. Hulet, “Fermions in Optical Lattices”, Latin American Optics and Photonics Conference (OSA), San Sebastiao, Brazil (11/12/12).

Randall G. Hulet, “Optical Lattice Simulations of Correlated Fermions”, DARPA OLE Workshop, Arlington, VA (11/8/12).

Randall G. Hulet, “Fermions in Optical Lattices”, Quo Vadis BEC? Meeting, Bad Honnef, Germany, (8/22/12).

W. Vincent Liu, Topological phases of fermions in the p-orbital band of optical lattices, 7th Cross-Strait and International Conference on Quantum Manipulation, 2013

W. Vincent Liu, Orbital phase transitions in low dimensional beyond-standard optical lattices, International Workshop on “Quantum Many-Body Systems in Low Dimensions”, 2013

W. Vincent Liu, Topological phases of fermions in the p-orbital band of optical lattices, NorditaWorkshop “Pushing the Boundaries with Cold Atoms", 2013

Xiaopeng Li, Orbital physics in one dimensional optical lattice, APS March Meeting, 2013

Ran Wei, Erich Mueller, Majorana fermions in one-dimensional spin-orbit coupled Fermi gases, APS March Meeting, 2013

Eliot Kapit, Erich Mueller, A Vector Potential for Flux Qbits, APS March Meeting, 2013

Yariv Yanay, Erich Mueller, Superfluid Density of Weakly Interacting Bosons on a Lattice, DAMOP, 2013

Erich Mueller, Majorana fermions in one-dimensional cold Fermi gases, International Workshop on “Quantum Many-Body Systems in Low Dimensions”, 2013

D. Weiss, Onset of thermalization in nearly integrable Bose gases, DAMOP, 2013

D. Weiss, Finite Temperature Non-Equilibrium Superfluid Systems, Queenstown, New Zealand, 2013

T.-L. Ho, ``Spin-Spiral States in 1D Fermi Gas at Infinite Repulsion", Hong Kong Forum, organized by University of Hong Kong, Dec 8, 2012

T.-L. Ho, ``Realizing the Pfaffian Quantum Hall State with Cold Atom
Magic", IAS Asia Pacific Workshop on Condensed Matter Physics, Dec
14-16, HKUST, Hong Kong

T.-L. Ho, "Novel States and Synthetic Gauge Fields of High Spin
Particles", ITAMP Workshop on Finite Temperature and Low Energy
Effects in Cold Atomic and Molecular Few and Many-body Systems. March
25-27, 2013

T.-L. Ho, ``Some Key Questions and Major Challenges in Cold Atom Research", Symposium in Spin-Orbit Effects in Cold Atoms, Xioa-Tung University, organized by Anthony Leggett, Shanghai April 20, 2013

T.-L. Ho, ``The World of High Spin Particles", 2013 Hongzhou Workshop on Quantum Matter, April 22-25, 2013

T.-L. Ho, ``Spin-orbit coupling in 1D Fermi gas with infinite repulsion", Workshop on Finite Temperature and Low Energy Effects in Cold Atomic and Molecular Few and Many-body Systems. " International Workshop on Quantum Many-Body Systems in Low Dimensions, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, June 19-21, 2013

T.-L. Ho, ``How weak spin-orbit interaction can cause dramatic many-body effects in low dimension systems", Workshop on ``Synthetic Gauge
Fields for Atoms and Photons", BEC Center, Trento, Italy, July 1-13,
2013

T.-L. Ho, ``Bosonic Quantum Hall States", An invited talk at Professor
Lev Pitaevskii's 80th Birthday Celebration, City Hall, Trento, Italy,
6 July 2013

C. J. Bolech, "Some results in the non-equilibrium expansion dynamics of integrable systems" The 7th annual Great Lakes Strings Conference.
University of Kentucky, Lexington (May 17th - 19th, 2013)

C. J. Bolech, "Non-equilibrium Dynamics in Low-dimensional Cold Atomic Gases". Physics at the Falls II: Recent Progress in Nonequilibrium Quantum Many-body Theory. State University of New York at Buffalo (May 16th - 18th, 2013)

Randall G. Hulet, “Observation of Antiferromagnetic Correlations in the Hubbard Model”, Seminar, International Center for Quantum Materials, Beijing, Peking University (6/12/14).

Randall G. Hulet, “Detection of Antiferromagnetic Correlations in the Fermi-Hubbard Model”, KITPC Workshop on Precision Many-Body Physics of Strongly Correlated Quantum Matter, Beijing (6/11/14).

Randall G. Hulet, “Detection of Antiferromagnetic Correlations in the Fermi-Hubbard Model”, APS DAMOP Annual Meeting, Madison, WI (6/3/14).

Randall G. Hulet, “Finite Range Corrections Near a Feshbach Resonance and their Role in the Efimov Effect”, Workshop on Few-Body Universality in Atomic and Nuclear Physics, Institute for Nuclear Theory, University of Washington, Seattle (5/12/14).

Randall G. Hulet, “Soliton Collisions: On the Edge of Integrability”, Joint ARO/AFOSR MURI Meeting, MIT (5/8/14).

Randall G. Hulet, “Simulating Quantum Magnetism with Atoms in Optical Lattices”, Pittsburgh Quantum Initiative on Quantum Technologies, University of Pittsburgh (4/9/14).

Randall G. Hulet, “Detection of Antiferromagnetic Correlations in the Hubbard Model”, Canadian Institute for Advanced Research (CIFAR) Workshop on Quantum Materials, Banff, Canada (2/9/14).

Randall G. Hulet, “Optical Lattice Simulations of Correlated Fermions”, DARPA OLE Workshop, Arlington, VA (2/11/14).

Randall G. Hulet, “Observation of Antiferromagnetic Correlations in the Hubbard Model”, Seminar, University of Sao Paulo, Sao Carlos, Brazil (12/10/13).

Randall G. Hulet, “Detection of Antiferromagnetic Correlations in the Hubbard Model”, BEC 2013, Frontiers in Quantum Gases, Sant Feliu, Spain (9/11/13).

Randall G. Hulet, “Detection of Antiferromagnetic Correlations in the Hubbard Model”, Aspen Center for Physics Workshop on Optical Lattices, Aspen (8/20/13).

Han Pu, "Quench Dynamics of a Spin-Orbit Coupled Fermi Gas", KITPC Program on Precision Many-Body Physics of Strongly Correlated Quantum Matter, Beijing, June, 2014

Han Pu, "Quench of a spin-orbit coupled Fermi gas", 6th International Symposium on Cold Atom Physics - ISCAP VI, Taiyuan, June, 2014

Han Pu, "Bogoliubov-de Gennes Study of Trapped Superfluid Fermi Gas", Workshop on Mathematical and Numerical Methods for Quantum, Kinetic and Nonlocal Problems, Beijing, May, 2014

Han Pu, "Single Impurity in Quantum Gases", ARO Workshop on Heavy Fermion Materials and Quantum Phase Transitions, Houston, Dec., 2013

Han Pu, "Impurities in Ultracold Fermi Gas", OSA's 97th Annual Meeting, Orlando, Oct., 2013

W. Morong, W. Shirley, and B. DeMarco, "Anderson localization in 2D using point-like disorder", DAMOP 2014.

W. McGehee, W. Xu, and B. DeMarco, "Spin Drag in the Disordered Hubbard Model", DAMOP 2014

D. Chen, C. Meldgin, and B. DeMarco, "Raman Cooling Quasimomentum in an Optical Lattice", DAMOP 2014

W. Xu and B. DeMarco, "Spectroscopy of Potassium Rydberg States via Electromagnetically Induced Transparency", DAMOP 2014.

B. DeMarco, "Evidence of Many-Body Localization in an Ultracold Atomic Hubbard Gas", Princeton Center for Theoretical Physics Workshop on Many-Body Localization, 2014.

B. DeMarco, "Ultracold Disordered Quantum Gases", University of Oklahoma Physics Colloquium, 2014.

B. DeMarco, "Out-of-Equilibrium Phenomena in Disordered and Hubbard Ultracold Gases", Gordon Research Conference on Correlated Electron Systems, 2014

“QMC Studies of Optical Lattice Emulators with Disorder,” U. Ray, C. Meldgin, P. Russ, B. DeMarco, D. Ceperley, DARPA OLE meeting 2014

“Probing the Bose-Glass-Superfluid Phase Boundary using Quantum Quenches of Disorder in an Optical Lattice,” C. Meldgin, U. Ray, P. Russ, B. DeMarco, D. Ceperley, DAMOP 2014

WV Liu, 6th International Symposium on Cold Atom Physics - ISCAP VI, Taiyuan, China. Invited talk: ”Orbital phases in beyond-standard optical lattices”, June 14-17, 2014

WV Liu, Army Science Planning & Strategy Meeting: Quantum Information and Sensing, Bolger Conference Center in Potomac, Maryland (Washington DC sub), invited talk: “Topological orbital physics of cold atoms in novel lattice geometries — a possible future direction for the Army”, Sep 24-25, 2013

WV Liu, “Cold Atoms” Summer School of Department of Physics, Tsinghua University, Beijing. Pedagogical lecture: “Selected Topics in Modern Many-Body Theory”, July 8-10, 2014

WV Liu, Remin University of China, Department of Physics Seminar: “Orbital phases beyond standard optical lattices”, May 21, 2014

WV Liu, Florida State University and National High Magnetic Lab, Tallahassee, Florida. Condensed Matter Physics Seminar: “Orbital phases in beyond-standard optical lattices”, Oct 25, 2013

Nikhil Monga, John Shumway, Kaden Hazzard, Erich Mueller, Steven Desch, "Renormalization of Bose-Hubbard Parameters from Few Body Correlations of Cold Atoms", APS March Meeting 2014

T.-L. Ho, "Creating bosonic quantum Hall states from fermionic ones through strong interaction", BEC 2013, San Feliu, Sept 9, 2013.

T.-L. Ho, "Frontiers and Challenges in Atom Research" , Colloquium, Georgia Tech University, Nov 4, 2013

T.-L. Ho, "Quantum Quenching", Workshop on Strongly coupled systems far away from equilibrium, Simons Center on Physics and Geometry, Stonybrook, Feb 24-28, 2014

T.-L. Ho, "Quantum Quenching in interacting Bose gas", MURI kickoff meeting, May 8-9, 2014

T.-L. Ho, "Finding New Principles and New State of Matter with Ultra-Cold Atoms" IAS Distinguished Lecture, Jocky Club Institute for Advanced Study, Hong Kong University of Science and Technology, June 25, 2014

C. Bolech, "Unconventional States and Geometric E?ects in Mesoscopic Systems of Ultra-cold Atomic Fermi Gases". The Fourth Conference on Nuclei and Mesoscopic Physics. National Superconducting Cyclotron Laboratory (NSCL), Michigan State University, East Lansing (May 5th-9th, 2014).

N. Trivedi, "Spin-orbit coupled bosons in an optical lattice", at the Workshop on Cold atoms as part of the Quantum Materials program of the Canadian Institute for Advanced Research, February 19-21, 2014.

N. Trivedi, "Prediction of a novel phase at intermediate coupling in a bose-fermi mixture", at the workshop on "Midwest Cold Atom Workshop", University of Purdue, November 16, 2013.

N. Trivedi, "From superfluids to optical lattices and quantum materials", at the workshop on "Condensed Matter Physics in the city at Royal Holloway, Hubbard Theory Consortium, London, UK, July, 2013.

VW Liu, Colloquium, Department of Physics, College of William & Mary, Williamsburg, VA (Nov., 2014)

VW Liu, Colloquium, Department of Physics, SUNY Buffalo (Nov., 2014)

VW Liu, Invited Short Blackboard Talk, in “Gauge Fields in Condensed Matter, Ultracold atoms and beyond” Program, Aspen Center for Physics (Sept., 2014)

B. DeMarco, Intrinsic Relaxation Dynamics and Cooling in Optical-Lattice Hubbard Models, JQI Seminar, 9/2014

B. DeMarco, Ultracold Disordered Quantum Gases, University of Maryland Physics Colloquium, 9/2014

C. Bolech, Bose-Hubbard Model with Occupation-parity Couplings and its Realization in Fermi Gases. Australasian Workshop on Emergent Quantum Matter 2014, Moreton Bay Research Station, North Stradbroke Island, Australia (November 24th - 28th, 2014).

C. Bolech, Bose-Hubbard Model with Occupation-parity Couplings and its Realization in Fermi Gases. Quantum Science Seminar, School of Mathematics and Physics, The University of Queensland, Brisbane, Australia (December 2nd, 2014).

C. Bolech, Expansion Dynamics vs. Geometric Quench. Technical Presentation, School of Mathematics and Physics, The University of Queensland, Brisbane, Australia (December 2nd, 2014).

C. Bolech, Finding Ground States for Quantum Systems in a 1D Continuum via Variational Matrix-Products Ansaetze. Midwest Numerical Analysis Day 2015. Wright State University, Dayton, OH (April 25th, 2015).

C. Bolech, Matrix-product Ansatz for Fermions in a 1D Continuum. Session on Quantum Many-Body Systems and Methods I. APS March Meeting 2015 (San Antonio, TX).

Randall G. Hulet, "Antiferromagnetism with Ultracold Atoms", Colloquium, Max Planck Institute for Quantum Optics, Munich (5/18/15).

Randall G. Hulet, "Observation of Antiferromagnetic Correlations in the Hubbard Model with Ultracold Atoms", Institute for Nuclear Theory Program on Quantum Simulation with Cold Atoms, University of Washington, Seattle (4/1/15).

Randall G. Hulet, "Observation of Antiferromagnetic Correlations in the Hubbard Model with Ultracold Atoms", APS March Meeting, San Antonio (3/3/15).

Randall G. Hulet, "Antiferromagnetism with Ultracold Atoms", Joint Quantum Institute Seminar, University of Maryland, College Park (1/26/15).

Randall G. Hulet, "Antiferromagnetism in the Hubbard Model with Ultracold Atoms", Congress of the Australian Institute of Physics, Canberra, Australia (12/8/14).

Randall G. Hulet, "Antiferromagnetism in the Hubbard Model with Ultracold Atoms", Workshop on Control of quantum correlations in tailored matter, Reisenburg Castle, Germany (10/7/14).

Randall G. Hulet, "Antiferromagnetism in the Hubbard Model with Ultracold Atoms", Physics Colloquium, University of British Columbia, Vancouver (9/11/14).

Randall G. Hulet, "Observation of Antiferromagnetic Correlations in the Hubbard Model", Workshop on Quantum Critical Matter – from Atoms to Bulk, Obergurgl, Austria (8/21/14).

T.L. Ho, "Gauge fields in cold atoms", Aspen Physics Center, August 2014.

T.L. Ho, "Cold Atoms in Curved Space", Quantum Materials-Perspectives and Opportunities, The Rice Center for Quantum Materials, December 15, 2014

T.L. Ho, "Cold Atoms in Curved Space", Celebration of 90th Birthday of Professor Li Cheng, Institute for Advance Study, Jan 5, 2015

T.L. Ho, "Realizing bosonic Quantum Hall states from fermionic ones using Feshbach resonance", JILA, Jan 15, 2015

T.L. Ho, "Quantum Quenching of Bose Gas to Unitarity", JILA, Jan 16, 2015

T.L. Ho, "Quantum Hall states in Cold Atoms": Tutorial, APS March Meeting, March 1, 2015

T.L. Ho, "Cold Atoms in Curved Space", INT workshop on Frontiers of Quantum Simulation with Cold Atoms, April 16, 2015

T.L. Ho, "Quantum Gases in Curved Space", ECT workshop on Interface between Cold Atom and High Energy Physics, June 22, 2015

T.L. Ho, "Cold Atoms in topological bands", Gordon Conference, Hong Kong University of Science and Technology, June 29, 2015

T.L. Ho, "Quenching Bosons to Unitarity", Workshop on Topological Matter, Celebration of 30 years Anniversary of IAMS, June 8, 2015

T.L. Ho, "Interacting Atoms in topological bands", Sino-German Conference in Cold Atoms, August 20, 2015

T.L. Ho, "Cold Atom research and Ultra-low temperature physics", NSF Workshop on Grand Challenges on Quantum Fluids and Quantum Gases, University of Buffalo, August 7, 2015

T.L. Ho, "Quenching Bose gases to Unitarity", Recent Progress in Many-Body Theory, Niagara Falls, August 17, 2015

T.L. Ho, “Quantum Gases in Curve Space”, Celebration of the 80th birthday of Professor Gordon Baym, UIUC, August 16, 2015

Number of Presentations: 115.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
07/31/2014	29.00	Russell A. Hart, Pedro M. Duarte, Tsung-lin Yang, Xinxing Liu, Thereza Paiva, Ehsan Khatami, Richard T. Scalettar, Nandini Trivedi, David A. Huse, Randall G. Hulet. Observation of antiferromagnetic correlations in the Hubbard model with ultracold atoms, arXiv:1407.5932 (07 2014)
07/31/2014	43.00	Eric Duchon, Yen Lee Loh, Nandini Trivedi. Optical Lattice Emulators: Bose and Fermi Hubbard Models, arXiv:1311.0543 (11 2013)
07/31/2014	39.00	Bo Zhao, Merritt C. Kerridge, David A. Huse. Three `species' of Schrödinger cat states in an infinite-range spin model, arXiv:1310.4992 (10 2013)
07/31/2014	37.00	Xiong-Jun Liu, Zheng-Xin Liu, K. T. Law, W. Vincent Liu, T. K. Ng. Chiral Topological Orders in an Optical Raman Lattice, arXiv:1405.3975 (05 2014)
07/31/2014	36.00	Bo Liu, Xiaopeng Li, Biao Wu, W.Vincent Liu. p-wave chiral superfluidity from an s-wave interacting atomic Fermi gas, arXiv:1402.5995 (02 2014)
07/31/2014	33.00	N. Tubman , ChangMo Yang . Direct calculation of the Entanglement Spectrum in Quantum Monte Carlo with application to \textit{ab initio} Hamiltonians, arXiv:1402.0503 (02 2014)
07/31/2014	31.00	Hui Hu, Lin Dong, Ye Cao, Han Pu, Xia-Ji Liu. Gapless topological Fulde-Ferrell superfluidity induced by in-plane Zeeman field, arXiv:1404.2442 (04 2014)
07/31/2014	30.00	Ying Dong, Lin Dong, Ming Gong, Han Pu. Dynamical topological phases in quenched spin-orbit coupled degenerate Fermi gas, arXiv:1406.3821 (06 2014)
09/04/2013	12.00	Xiaopeng Li, W. Vincent Liu, Leon Balents. Spirals and skyrmions in two dimensional oxide heterostructures, arXiv:1308.4179 (08 2013)
09/04/2013	13.00	David A. Huse, adim Oganesyan. A phenomenology of certain many-body-localized systems, arXiv:1305.4915 (05 2013)
09/04/2013	14.00	Hyungwon Kim, David A. Huse. Ballistic spreading of entanglement in a diffusive nonintegrable system, arXiv:1306.4306 (06 2013)
09/05/2013	22.00	Xiaoling Cui, Tin-Lun Ho. Ground-State Ferromagnetic Transition in Strongly Repulsive One-Dimensional Fermi Gases, arXiv:1305.6361 (05 2013)

TOTAL: **12**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter
09/04/2013 11.00	. The Fermi Gases and Superfluids: Short Review of Experiment and Theory for Condensed Matter Physicists, : , ( )
TOTAL:	**1**

Patents Submitted

Patents Awarded

Awards

Brian DeMarco: University of Illinois Willett Scholar Award, 2013

Han Pu: APS Outstanding Referee, 2013

Han Pu, elected as APS fellow, 2013

David Ceperley, elected to the International Academy of Quantum Molecular Science

Erich Mueller: Robert A. and Donna B. Paul Academic Advising Award

Tin-Lun Ho: elected to American Academy of Arts and Sciences, 2015

Erich Mueller: elected as APS fellow, 2014

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Tsung-Lin Yang	1.00	
Xinxin Liu	0.30	
Ramachandhran Balasubramaniar	0.20	
David Chen	0.75	
Wenchao Xu	0.45	
Hyungwon Kim	0.50	
Bo Zhao	0.15	
Biao Huang	1.00	
Weiran Li	1.00	
Sayan Choudhury	0.15	
Shovan Dutta	1.00	
Bhuvanesh Sundar	0.13	
Yariv Yanay	0.85	
Laura Zundel	0.20	
ChangMo Yang	1.00	
Ushnish Ray	1.00	
Sangwoo Chung	1.00	
William Cole	1.00	
Timothy McCormick	1.00	
Ian White	0.50	
Phlip Russ	0.50	
Wenchao Xu	0.75	
Willam McGehee	0.80	
William Morong	0.20	
Ran Wei	0.68	
Zhongtao Mei	0.50	
Cheng Li	1.00	
Tim McCormick	1.00	
Jacob Fry	0.00	
FTE Equivalent:	**18.61**	
Total Number:	**29**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Russell Hart	1.00
Benjamin Olsen	1.00
Bo Liu	0.20
Stephan Mandt	0.10
Kuei Sun	1.00
David Nozadze	1.00
Marco Schiro	0.33
Lin Xia	0.50
Jean-Felix Riou	0.10
Zhifang Xu	0.05
Haiyuan Zou	0.05
Maksims (Max) Arzamasov	0.05
FTE Equivalent:	**5.38**
Total Number:	**12**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Randall G. Hulet	0.08	No
Han Pu	0.08	
Brian DeMarco	0.08	
David Huse	0.08	
Tin-Lun Ho	0.08	
Vincent Liu	0.08	
Carlos Bolech	0.08	
Erich Mueller	0.08	
David Ceperley	0.08	
Nandini Trivedi	0.08	
FTE Equivalent:	**0.80**	
Total Number:	**10**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Arun Nanduri	0.00	physics
Merritt Kerridge	0.00	physics
Michael DeMarco	0.00	physics
FTE Equivalent:	**0.00**	
Total Number:	**3**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ......

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ......

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ......

Names of Personnel receiving masters degrees

NAME	
Melissa Revelle	
Lin Dong	
Tsung-Lin Yang	
Total Number:	**3**

Names of personnel receiving PHDs

NAME	
Xiaopeng Li	
Hong Lu	
Weiran Li	
Ramanchandhran Balasubramanian	
Pedro Duarte	
Total Number:	**5**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Final Report for period Nov. 15, 2012 – Jan. 14, 2015
DARPA Optical Lattice Emulator Program

Quantum Phases of Matter in Optical Lattices
ARO W911NF-13-1-0018

Han Pu, Randall Hulet, Rice University
David Ceperley, Brian DeMarco, University of Illinois
Jason Ho, Nandini Trivedi, Ohio State University
David Huse, Princeton University
W. Vincent Liu, University of Pittsburgh
Erich Mueller, Cornell University
Carlos Bolech, University of Cincinnati
David Weiss, Penn State University

Prepared May 30, 2015 by Han Pu and Randall Hulet

Abstract

Ultracold atoms confined in optical lattice potentials provide an ideal platform to address some of the most outstanding questions in quantum many-body physics, that are difficult or impossible to study using conventional solid state systems. During this DARPA program, progress in several important directions has been made. We have developed cooling techniques suitable for a lattice system and cooled fermionic lithium atoms confined in a three-dimensional (3D) cubic lattice to unprecedented low temperatures, very close to the Néel temperature. We employed Bragg scattering of near-resonant light to observe the antiferromagnetic correlations. We have mapped the phase diagram over the entire BEC-BCS crossover for a trapped 3D gas with imbalanced numbers of spin-up and spin-down atoms, and have also observed the crossover from a 1D to a 3D spin-imbalanced Fermi gas. We have investigated dynamics, rethermalization and out-of-equilibrium phenomena in strongly correlated lattice systems, as well as in disordered lattice systems. These studies greatly deepened our understanding of quantum phases of matter in lattice potentials.

During this funding period, significant progresses have been made by our team, several milestones have been reached, and new research directions have been identified. The following is a summary of our research achievements made possible by the DARPA funding.

3D Fermi-Hubbard Model and antiferromagnetism

The Hulet group, in collaboration with theory groups led by Huse, Scalettar and Trivedi, have used Bragg scattering of light to detect antiferromagnetic correlations in a three-dimensional (3D) optical lattice with densities near 1 atom/site. This was accomplished by preparing the atoms at temperatures of 1.4 T_N, where T_N is the Néel temperature. This is a factor of two below the previously reported lowest temperatures for atoms in a lattice. By comparing the Bragg signal to quantum Monte Carlo (QMC) calculations, they realized thermometry in the lattice that is accurate at the 10% level. The closed black circles in Fig. 1a are the trap-averaged Bragg signal for several values of U/t, where U is the onsite interaction and t is the nearest neighbor tunneling rate. The colored lines in Fig. 1a are the results of QMC for several values of scaled temperature T/t. Figure 1b shows the calculated Bragg signal vs. T/t as open diamonds, while the grey area is the uncertainty range for the measured Bragg signal. The data fit best to T/t = 0.50. In comparison, T_N/t maximizes at 0.36.

The development of a novel "compensated" optical lattice was essential for the success of this experiment. The compensated lattice uses blue-detuned anti-confining beams superimposed on each of the infrared lattice beams to offset the inhomogeneous confinement envelope of the bare lattice. Compensation provides: 1) a way to adjust the density; 2) cooling (or mitigated heating) in the lattice by evaporation; and 3) a flattening of the inhomogeneous band structure produced by the lattice confinement.

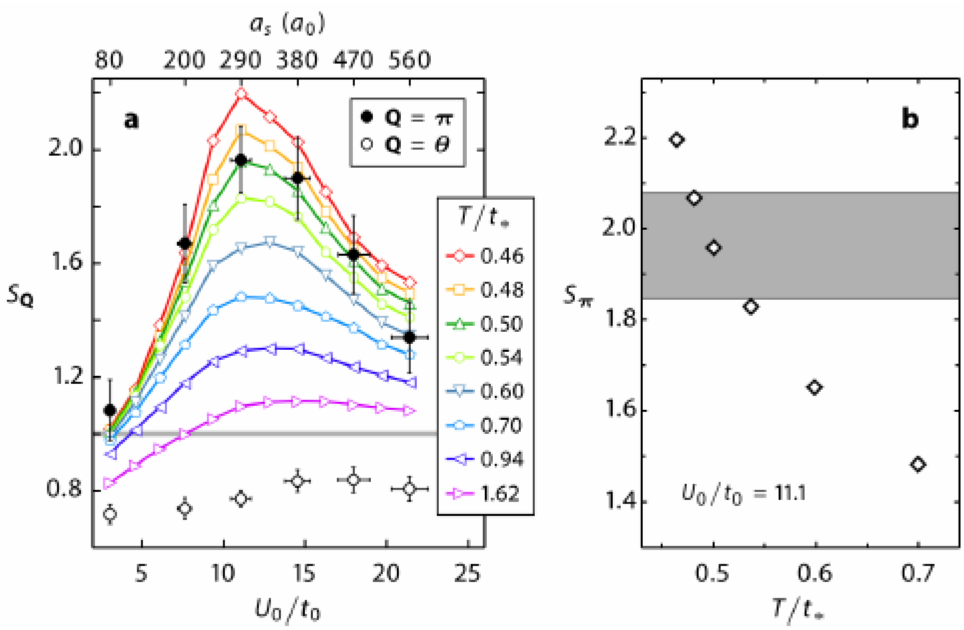


Figure 1. a) Closed circles are the trapped-average Bragg signal S_Q (related to the static structure factor) for Q = π, a reciprocal lattice vector for antiferromagnetic order and the open circles correspond to an arbitrary Q, which is not Bragg enhanced. The colored lines are the result of QMC for the various temperatures indicated. b) QMC (open diamonds) and the uncertainty range of the measured Bragg signal showed in grey. The best fit to the data is T/t = 0.50.

The antiferromagnetic phase is also expected to be a Mott insulator. With exactly one atom per lattice site, the compressibility of the Mott phase goes to zero. They explored the Mott phase using *in-situ* imaging of the density distributions. An example of the column density distribution directly recorded in these images is shown in Fig. 2a, while the inverse Abel transform, which reconstructs the three-dimensional distribution is shown in Fig. 2b. These distributions have the characteristic flat-top of the Mott phase. A Mott plateau, such as this one, had not been clearly resolved in the past for fermions.

Since this data was obtained, they have improved the stability of the compensated lattice. Better stability will enable us to better optimize the compensated lattice for cooling to lower temperatures. If successful, they will explore the critical regime at the phase transition, and obtaining even lower temperatures may open up the possibility of observing *d*-wave superfluidity, which has been conjectured to provide the mechanism for high temperature superconductors.

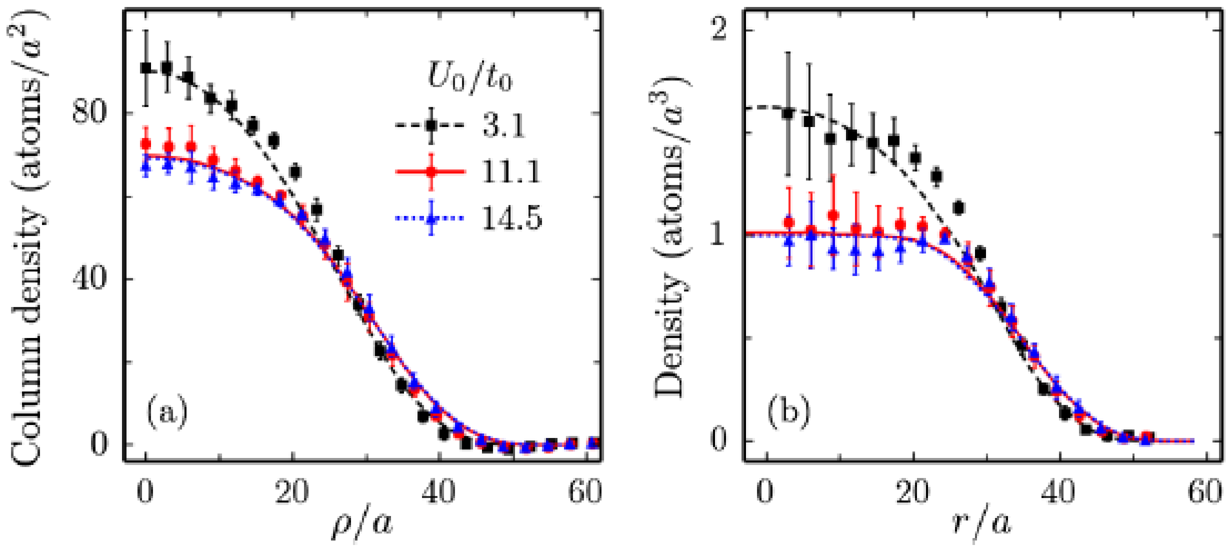


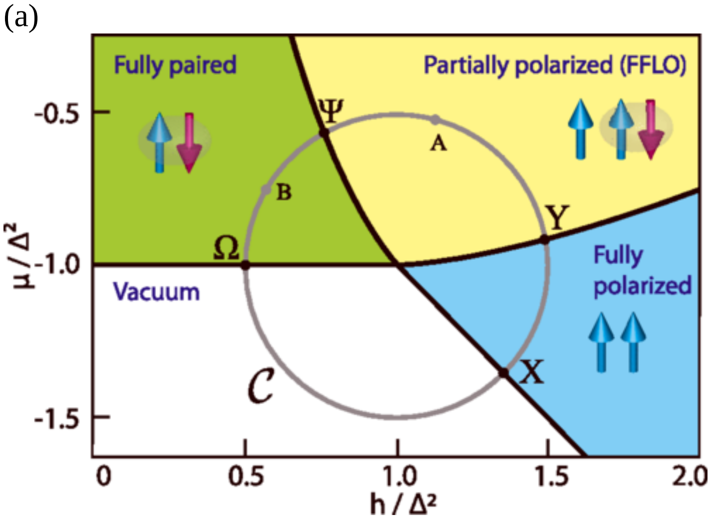
Figure 2. *In-situ* images of a 3D optical lattice for various interaction strengths. a) column densities; and b) reconstructed three-dimensional distributions showing Mott plateaus for stronger interactions. The large number of atoms in the Mott phase is a result of the flattening of the lattice band using the compensated lattice. The atoms in the Mott phase develop antiferromagnetic correlations at sufficiently low temperature.

Spin-imbalanced two-component Fermi gas

Hulet's group have also made great progress on the experimental study of spin-imbalanced fermions. They have mapped the phase diagram over the entire BEC-BCS crossover for a trapped 3D gas with imbalanced numbers of spin-up and spin-down atoms. A manuscript reporting these results is nearing completion. They have also now observed the crossover from a 1D to a 3D spin-imbalanced Fermi gas. This experiment uses a two-dimensional optical lattice to create a bundle of 1D tubes. As the lattice depth is decreased, the coupling between tubes is enhanced, leading to a crossover from a 1D to a 3D phase diagram. They have found experimentally that the location of the dimensional crossover is universal, such that data for different interaction strengths and lattice depths cross from 1D to 3D at the same value of t/ε_b, where t is the hopping strength between tubes and ε_b is the binding energy of the pairs in the 1D tube. The elusive FFLO state is predicted to be stabilized near this crossover, so their next experiment will be to search for the expected domain boundaries that are potentially observable in a time-of-flight experiment.

Several theory groups have worked on this topic. Pu's group considered an attractive two-component Fermi gas with Raman-induced spin-orbit coupling, and showed that under certain situations, the Cooper pairs naturally possess finite momentum as a result of the interplay between spin-orbit coupling, spin imbalance induced by the effective Zeeman field, and interaction. Recently, Bolech's group has extended the continuous matrix product states (cMPS) to nonrelativistic fermions and shown that the cMPS, correctly describes the ground-state superfluid and magnetic properties of interacting Fermi gases in 1D, as those realized in Hulet's lab. This includes the signatures of a partially polarized superfluid regime (FFLO), in agreement with the large amount of theoretical and experimental work from the DARPA-team effort. The new type of ansatz promises to be ideally posed to be able to describe atomic gases in optical lattices economically but without making a lattice-model (tight-binding) approximation, and should be able to extend the theoretical predictions for these systems beyond the current limitations. Figure 3 illustrates the results of this work.

(a)



(b)

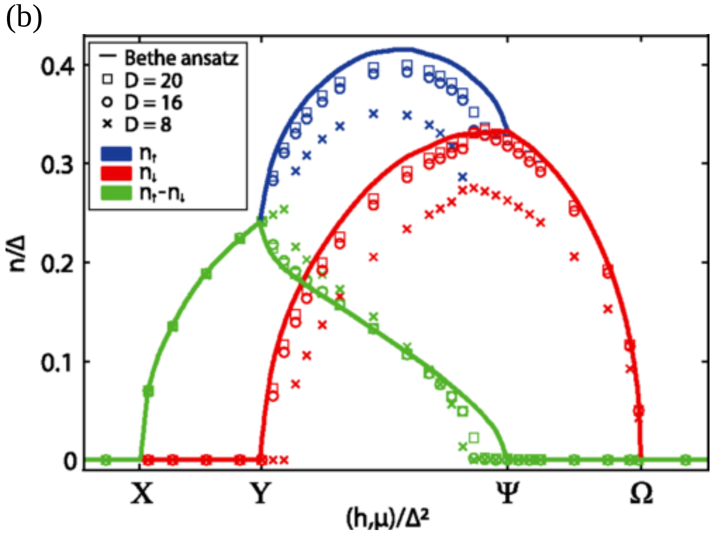


Figure 3. (a) Zero temperature ground-state phase diagram for the homogeneous attractive spin-1/2 Fermi gas in 1D. The phase boundaries were obtained from the Bethe ansatz. The points X, Y, Ψ, and Ω along the circular trajectory C denote the intersections with the phase boundaries. (b) Densities of the majority spins n↑ (blue),

minority spins n↓ (red), and their difference n↑−n↓ (green) along the trajectory C in (a), as obtained from variational states having bond dimensions D=8, 16, 20 and the exact Bethe ansatz result (solid curve).

Liu's group also carried out a study of cold fermions in optical lattices with spin imbalance theoretically. The predict the existence of chiral superfluidity with **p**-wave symmetry from an **s**-wave interaction. Chiral **p**-wave superfluids are fascinating topological quantum states of matter that have been found in the liquid 3He-A phase and arguably in the electronic Sr2RuO4 superconductor. They are fundamentally related to the fractional 5/2 quantum Hall state, which supports fractional exotic excitations. Past studies show that they require spin-triplet pairing of fermions by **p**-wave interaction. Here the key idea Liu's group proposed is that pairing of fermions takes place between **s** and **p** orbitals of the optical lattice (see Fig. 4), which have even and odd parity, respectively. A crucial condition for realizing such pairing is to create sufficiently large spin imbalance so that the spin up and down Fermi levels reside in the **s** and **p** orbital bands, respectively, with total fermion numbers N_up < N_down. This **p**-wave state is conceptually distinct from all previous conventional **p**-wave states as it is for the center-of-mass motion, instead of the relative motion. It leads to spontaneous generation of angular momentum, finite Chern numbers and topologically protected chiral fermionic zero modes bounded to domain walls, all occurring at a higher critical temperature in relative scales, due to the *s*-wave pairing nature in relative motion.

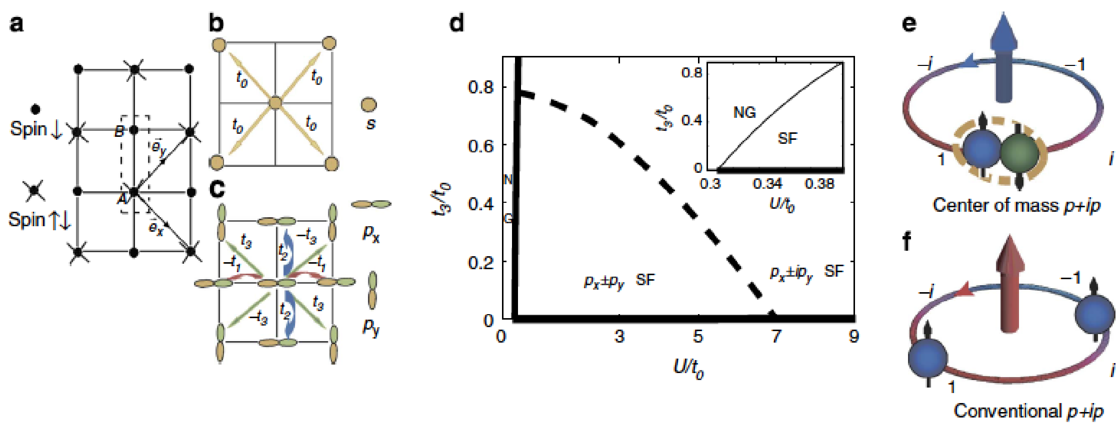


Figure 4. (a) Schematic picture of a 2D spin-dependent optical lattice, where the spin up (s orbital band) and down (p orbital band) component lying within different geometry lattice potential, respectively. Here A and B stand for two different sites in one unit cell,~ex and~ey are the primitive unit vectors. (b and c) Schematic views illustrate tunneling t0, t1, t2 and t3 of fermions prepared in the s and p orbitals, respectively. (d) Zero-temperature phase diagram when t1/t0¼8, t2/t0¼2—The solid line illustrates the phase transition from normal gas (NG) to superfluid state (SF). When U/t0o7, the critical value of t3/t0 as shown by the dash line, beyond this threshold a phase transition from px±py to px±ipy superfluid state occurs. When U/t0Z7, px±ipy superfluid state is the ground state with non-zero t3. The thick solid line stands for a two-component superfluid state. (e and f) Pictorially illustrate the distinction between centre-of-mass and conventional pþip pairings. Here, the character of pþip pairing states is demonstrated by the phase of the superconducting gap labelled by the color of the torus. In e, the Cooper pair is a spin-singlet pair composed of two spin species fermions and has finite centre-of-mass orbital angular momentum, whereas in f it is a conventional spin-triplet pair formed by single species fermions and has conventional relative motion angular momentum.

Dynamics and Out-of-Equilibrium phenomena

If one wants to experimentally study an equilibrium phase diagram, the system must be in equilibrium. During the OLE project, we realized that this tautology represented one of the most challenging aspects of the OLE program. Great efforts have been made to understand the dynamic processes which drive an optical lattice system to equilibrium.

DeMarco and Ceperley collaborated on two results involving dynamics and out-of-equilibrium phenomena in strongly correlated optical lattices. The first focused on measurements and simulations of the peak fraction for a Bose-Einstein condensate loaded into a cubic optical lattice. DeMarco's group measured how peak fraction varied as the entropy per particle of the gas and the lattice potential depth were varied in the superfluid regime (Fig. 5). These measurements were compared with large-scale, exact quantum Monte Carlo simulations carried out by Ceperley's group. A discrepancy was discovered at high temperatures—the experimentally measured peak fraction was too high for a gas in thermal equilibrium in the lattice. An explanation for this phenomenon in terms of suppression of Landau damping (Fig. 6) was found in collaboration with Stefan Natu at the JQI. These results were published in Physical Review A **91**, 023625 (2015) and highlighted as an Editor's Suggestion. The suppression of thermalization observed in this system has critical implications for optical lattice experiments.

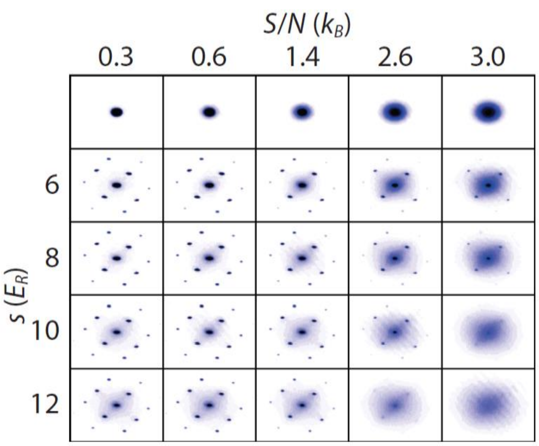


Figure 5. Images taken of ultracold atoms prepared at difference entropies per particle S/N after turning on an optical lattice to depth s.

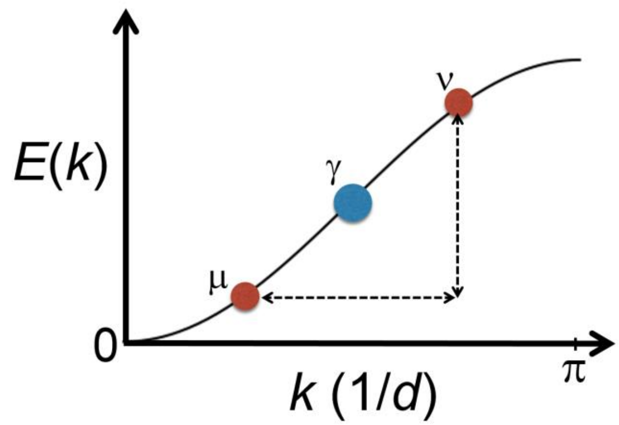


Figure 6. Schematic diagram of Landau damping, whereby a quasiparticle (γ) can decay to two particles (μ and ν).

DeMarco's and Ceperley's groups also collaborated on a project to understand the analog of the Kibble-Zurek scenario for a disorder quench. DeMarco's group measured excitations generated by quenching disorder for a superfluid loaded into a disordered optical lattice (Fig. 7). A threshold disorder required to generate excitations was found and compared with the disorder required to create a Bose-glass phase in exact quantum Monte Carlo simulations carried by Ceperley's group. These QMC simulations are the most complex and largest scale ever carried out for a disordered system. Both qualitative and quantitative agreement between the onset of excitations in the experiment and Bose-glass in the simulations was demonstrated (Fig. 8). This behavior is evidence that the Kibble-Zurek mechanism may apply to quantum phase transitions in disordered systems, which is an important issue for approaches such as adiabatic quantum computing. This work is available as a preprint (arXiv: 1503.02333 (2015)).

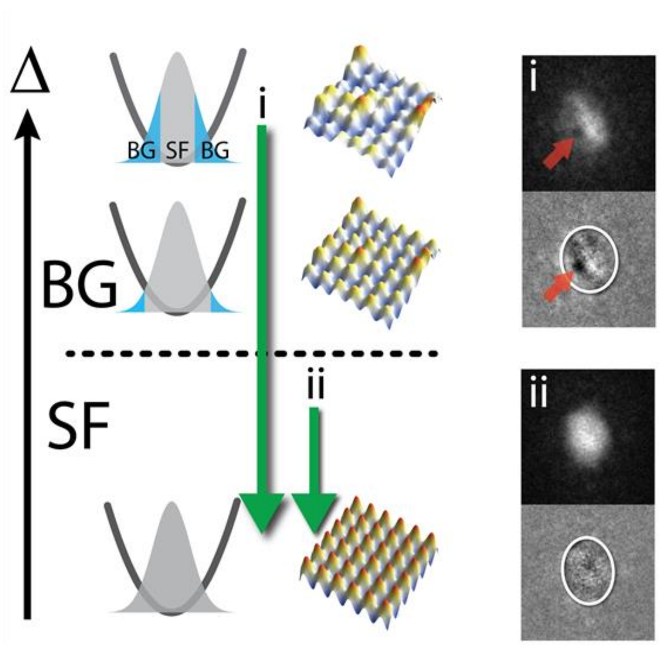


Figure 7. Quenching procedure carried out by DeMarco's group. The disorder strength Δ is rapidly reduced. For sufficient disorder, excitations such as vortices are created during the quench (i), while excitations are absent at lower Δ (ii).

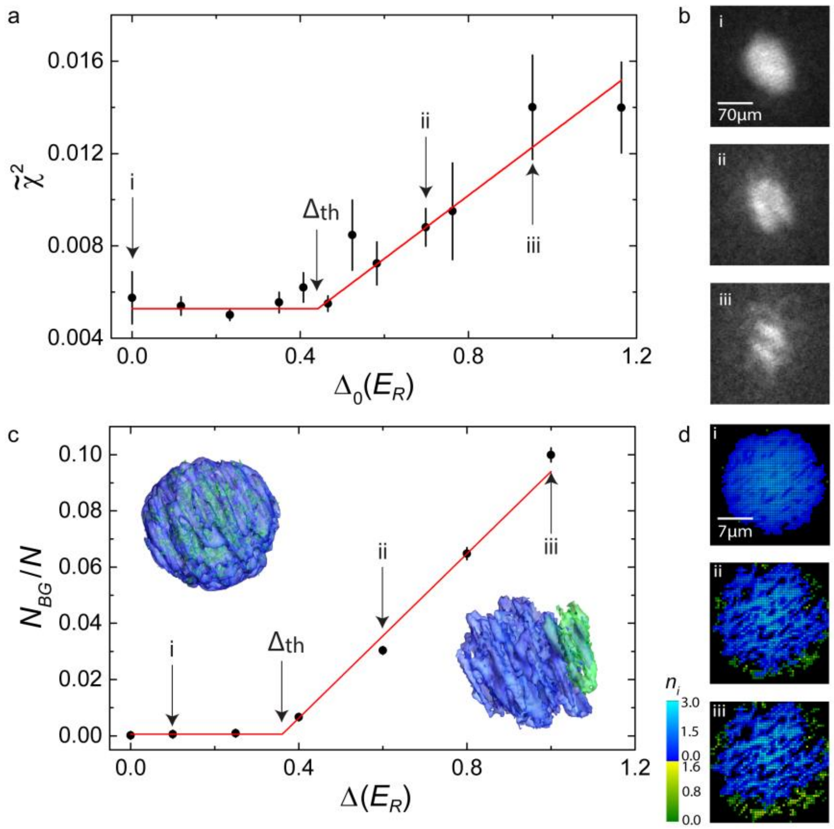


Figure 8. Comparison of excitations measured in the experiment (a) and the fraction of Bose-glass atoms in the simulations (c). The inset to (c) shows the lowest two occupation eigenfunctions of the single-particle density matrix for Δ=0 (left) and Δ=1 ER (right). Images of excitations generated in the experiment are shown in (b), and simulations of the occupation for atoms in superfluid (blue) and Bose-glass phases (green) are shown in (d).

DeMarco and Mueller collaborated on an effort to understand rethermalization for bosons trapped in a strongly correlated optical lattice. They found that phase coherence is more robust than one would naively expect. One can maintain equilibrium during ms ramps, even though the characteristic hopping time is an order of magnitude larger. This is good news for exploring equilibrium physics, and is due to the role of interactions. DeMarco's group developed a method for rapidly bringing the quasimomentum distribution of the gas out of equilibrium (Fig. 9). The re-equilibration time of a thermal gas was measured for different lattice potential depths in the superfluid regime. Rapid thermalization and a strong violation of the Mott-Ioffe-Regel criterion was observed, which rules out Boltzmann transport approaches to understanding thermalization. Similar effects have been observed, but not understood, in strongly correlated electron solids. Mueller modeled the rethermalization process using a simple quantum approach. Agreement with no free parameters between the measurements and model was found for high lattice depths (Fig. 10). These measurements are important to efforts to cool atoms in lattices and may shed light on unusual diffusion and transport phenomena in solids. These results are available as a preprint (arXiv: 1503.07606 (2015)) and are under review for publication in *Nature Physics*.

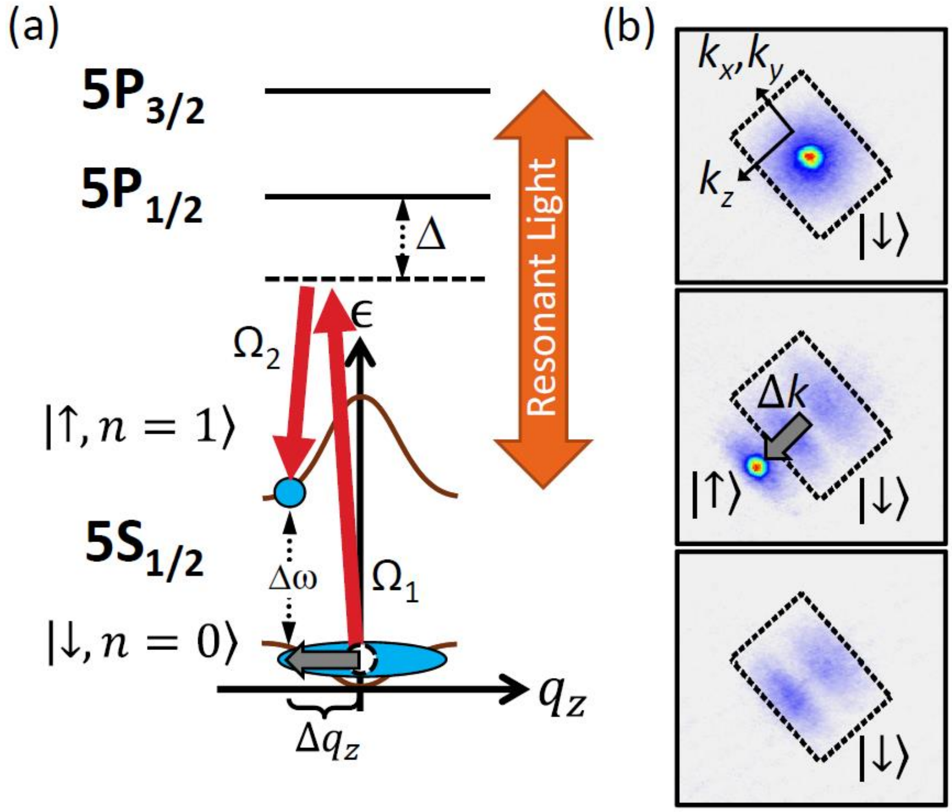


Figure 9. Procedure to disrupt equilibrium using stimulated Raman transitions developed by DeMarco's group (a). Images of the gas taken after turning on the lattice (top) and after removing atoms (bottom) are shown in (b).

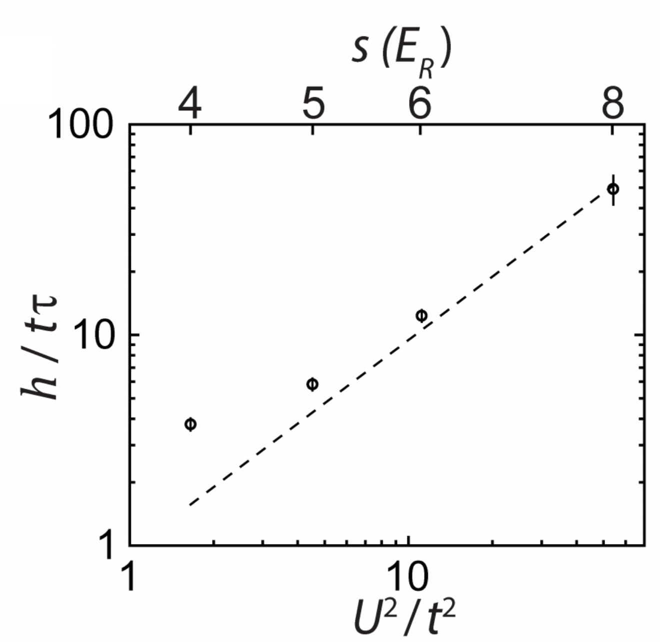


Figure 10. Measured rethermalization rate τ normalized to the tunneling time h/t for different lattice potential depths s. The quantum model of thermalization is shown as dashed line.

Other Theoretical Issues

In addition to those mentioned above, our team have explored various theoretical issues that are not necessarily directly tied to the experiments carried out in the experimental groups within our team, but are broadly related to the OLE program.

Several groups have explored topological phases in ultracold atoms subject to spin-orbit coupling (SOC). Pu' group has investigated properties of both bosonic and fermionic systems with spin-orbit coupling. They also proposed to create SOC with quantized light field supported by an optical cavity, where the atomic feedback onto the cavity field give rises to a dynamic SOC. Mueller's group has investigated ways of studying "topological phases" in an optical lattice experiment. These are exotic states which may have application in spintronics or quantum computing — and which have become an area of intense study over the past decade. They conducted theoretical investigations into the possibility of observing these states in cold atom experiments. At the moment there are still technical difficulties which make such experiments challenging, but these works (and related ones from other authors) show that cold atom experiments have advantages over solid-state experiments for directly observing some of the more exotic features of these states. For example, they showed that radio waves can manipulate the non-local quantum correlations that these states possess. Ho's group has also studied interaction effects in spin-orbit coupled quantum gases, and larger spin fermions with SOC. They have shown that spin-orbit coupled large spin fermions possess very rich spin structures, some of which have the symmetry of a Platonic solid, and many have non-Abelian line defects. In addition, they continue to make significant headway in the following problems: (a) cooling of the spin degrees of freedom of lattice quantum gases, and (b) topological matter caused by external fields and by interaction effects.

Mueller's group also carried out studies of the feasibility of observing Nagaoka ferromagnetism in an optical lattice [Yariv Yanay, Erich Mueller, Veit Elser, Magnetic polarons in two-component hard core bosons, Phys. Rev. A 87, 043622 (2013)]. This is a phase of an iconic magnetic model which was used in the 60's to develop understanding about various mechanisms for ferromagnetism. Experimentally studying this phase is an important piece of validating theoretical techniques which are being applied to transition-metal-oxides. They found that a "quantum gas microscope" experiment on cold bosons could readily observe the development of ferromagnetic order.

Several groups have extended this DARPA funded research into other directions. due to the questions from the leaders in other communities, Ho has begun to think about extending the Quantum Simulation Program of cold atoms to other disciplines (from the traditional ultra-low temperature Helium physics to lattice gauge field theory in high energy physics), as well as the common challenges of these different fields. For example, he has started new investigations of quantum gases in curved space and the highly non-equilibrium phenomena of inflationary expansion of quantum gases. In a related study, Mueller has found that when one changes parameters faster than the equilibration times, "coherence waves" spread ballistically through the atomic cloud (see Fig. 11). As pointed out by Hung *et al.* [Science 341, 1213 (2013)], these waves are visible in experiments, and are analogous to structures seen in spatial maps of the black-body radiation spectrum: In the expansion phase of the early universe, the size of the universe changed faster than any equilibration times.

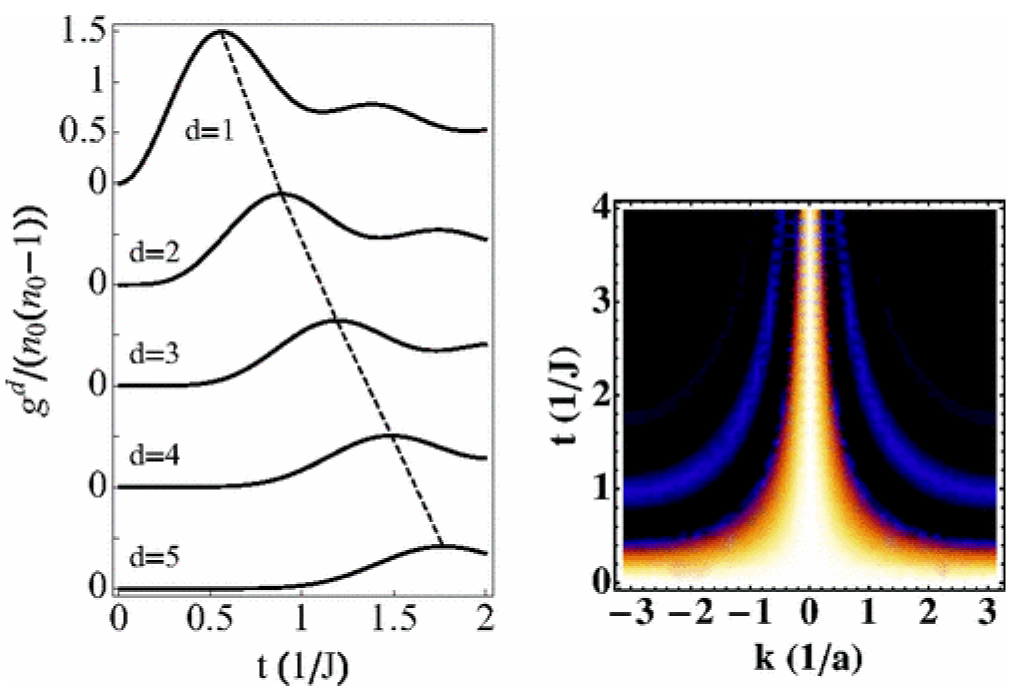


Figure 11. Illustration of coherence wave following a quench into the superfluid state.